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On the alignment of debris disks and their host stars' rotation axis – implications for spin-orbit misalignment in exoplanetary systems

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ABSTRACT

It has been widely thought that measuring the misalignment angle between the orbital plane of a transiting exoplanet and the spin of its host star was a good discriminator between different migration processes for hot-Jupiters. Specifically, well-aligned hot-Jupiter systems (as measured by the Rossiter-McLaughlin effect) were thought to have formed via migration through interaction with a viscous disc, while misaligned systems were thought to have undergone a more violent dynamical history. These conclusions were based on the assumption that the planet-forming disc was well-aligned with the host star. Recent work by Lai et al. has challenged this assumption, and proposes that the star-disc interaction in the pre-main sequence phase can exert a torque on the star and change its rotation axis angle. We have estimated the stellar rotation axis of a sample of stars which host spatially resolved debris disks. Comparison of our derived stellar rotation axis inclination angles with the geometrically measured debris-disk inclinations shows no evidence for a misalignment between the two.

Key words: planetary systems – stars: activity – stars: rotation

1 INTRODUCTION

The discovery of planets beyond the confines of our Solar system has presented many surprises and continues to challenge our understanding of planet formation and their subsequent evolution. This is particularly true in the case of hot-Jupiters, whose short orbital periods of a few days or less was unexpected – under the standard core-accretion theory of planet formation, volatile gas-giants should form beyond the snow-line (Pollack et al. 1996). It is now widely accepted that hot-Jupiters did not form in-situ at their current locations, but that some mechanism caused their inwards migration towards their parent star.

A number of theories have been postulated to explain planetary migration. One possible mechanism for forming short-period gas-giants is the pumping of initially wide circular orbits to high eccentricities. This could occur via planet-planet scattering (Rasio & Ford 1996; Weidenschilling & Marzari 1996), or perturbations from a distant stellar binary companion (Eggenberger et al. 2004). The highly eccentric orbit then brings the gas-giant sufficiently close to the host star that tidal dissipation quickly draws the planet to a new, smaller orbital separation. In this scenario, the interactions and scattering involved may lead to large changes in the value of the orbital inclination. Interactions between the planet and a viscous disc, on the other-hand, may also drive the planet inwards but is not thought to perturb the initial orbital inclination.

The close alignment of the rotation and orbital axes in the Solar system (∼7°; Beck & Giles 2005) is attributed to the formation of the Sun and planets from a single rotating proto-stellar disc which was also initially coplanar to the solar-rotation axis. On the premise that discs and stellar

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rotation axes are aligned, Rossiter-McLaughlin (RM) observations of transiting systems (e.g. Triaud et al. 2010 and references therein) have sought to discriminate between migration caused by planet-disc interactions (leading presumably to aligned systems), and migrations involving some violent dynamical history (leading to misaligned systems). In a recent paper, however, Lai et al. (2010) present arguments that the observed star-orbit misalignment could instead result from alterations in the *stellar* spin axis, introduced by the star-disc interaction during the pre-main-sequence phase (also see Foucart & Lai 2010). This, potentially, has important ramifications for our interpretation of the results of RM observations. Indeed, if the stellar rotation axis can be driven from coplanarity with the surrounding disc then RM observations would essentially be rendered useless as a tool for determining the migration mechanism responsible for forming hot-Jupiter's.

Lai et al. consider the well known fact that a magnetic protostar exerts a warping force on the inner part of the accretion disc (e.g. Bouvier et al. 2007). Previous authors have assumed that this results in significant warps to the inner disc, whereas Lai et al. (2010) argue that viscous processes in the disc itself will smooth these torques, resulting in a largely unwarped inner disc. Given a flat disc, the torques arising from the star-disc interaction will act on the star itself, changing the stellar spin axis on a timescale given by

$$t_{spin} = (1.25\mathrm{Myr}) \left(\frac{M_*}{1M_\odot}\right) \left(\frac{\dot{M}}{10^{-8}M_\odot\mathrm{yr}^{-1}}\right)^{-1} \times \left(\frac{r_{in}}{4R_*}\right)^{-2} \frac{\omega_s}{\Omega(r_{in})}, \quad (1)$$

where M_* and R_* are the mass and radius (in solar units) of the protostar, respectively, $\dot{M}$ is the accretion rate in solar masses per year, r_{in} is the inner radius of the accretion disc in stellar radii, ω_s is the spin rate of the protostar and $\Omega(r_{in})$ is the rotation rate of the accretion disc at the inner disc radius.

However, the mechanism proposed by Lai et al. (2010) may not be effective in practice, as the timescale for spin evolution, t_{spin}, is of the same order as the disc evolution timescale. Near-infrared observations of protostars show that the majority of protostellar discs have dispersed by the age of 5 Myr (Hernández et al. 2008) whilst observations of the accretion rates onto young stars also show that the accretion rate declines rapidly with increasing age and decreasing stellar mass (e.g Sicilia-Aguilar et al. 2006), so the accretion rate on many protostars may well be below the canonical 10^{-8} $M_\odot\mathrm{yr}^{-1}$ assumed by Lai et al. (2010). In addition, the results of Lai et al. (2010) rely on the inner disc not being 'significantly warped', however there is good evidence that the inner discs of some young stars do contain significant disc warps (see e.g. Bouvier et al. 2007; Muzerolle et al. 2009).

For these reasons, it is important to seek observational evidence for the process suggested by Lai et al. (2010). In this paper we present a study of star-disc alignment in debris disc systems.

2 MEASURING THE STAR-DISK ALIGNMENT

For the purposes of this work, we have concentrated on systems with spatially resolved debris disks. The inclination of the disk to our line-of-sight can then be measured geometrically by calculating the fore-shortening of the semi-minor axis of the disk relative to the semi-major axis (although in reality the models used to determine the disc geometry are somewhat more complex).

A more indirect approach is needed in order to determine the inclination angle of the stellar rotation axis, however. To do this we have followed the method of Watson et al. (2010) who complied the stellar rotation inclination angles for 117 exoplanet host stars, and we refer the reader to that paper for in-depth details of the methods used, as well as a discussion on possible sources of systematic errors inherent in the technique. In summary, it is possible to determine the inclination angle, i, between the rotation axis of a star and the observers line-of-sight from measurements of the projected equatorial velocity ($v \sin i$), the stellar rotation period (P_{rot}) and the stellar radius (R_*) via the equation

$$\sin i = \frac{P_{rot} \times v \sin i}{2\pi R_*}. \quad (2)$$

The projected equatorial rotation velocity, $v \sin i$, can be measured using high-resolution spectroscopy, while the stellar radius can also be indirectly determined from spectra or, less frequently, directly via interferometry, lunar occultations or eclipses (e.g. Fracassini et al. 2001). Precisions on stellar radius measurements of ∼3 per cent are now regularly quoted (e.g. Fischer & Valenti 2005).

Determining the stellar rotation period, on the otherhand, tends to be more troublesome. For some active stars, the stellar spin period can be determined photometrically to high precision by tracking the passage of large star spots on their surfaces. For those systems which do not have photometrically measured rotation periods, measurements of Ca II H and K emission can be used to estimate the rotation period by applying the chromospheric emission – rotation period relationship of Noyes et al. (1984). Naturally, this latter method is less precise, and is also affected by intrinsic variability of the Ca II H and K emission due to, for example, solar-like activity cycles or the rotation of magnetic regions.

We have carried out an extensive literature search and present $v \sin i$, R_*, and P_{rot} estimates for a number of main-sequence stars which host spatially resolved debris disks in Table 1. Since one of the pre-requisites for measuring a stellar rotation period is that the star must be magnetically active, we are restricted to lower main-sequence stars later than ∼F5V which have a convective envelope (and are thereby capable of sustaining a stellar dynamo). Of the 20 main-sequence stars with resolved debris disks, only 10 have spectral types of F5V or later. Of these, we can find no recorded Ca II H and K emission measurement for HD 181327, and is therefore omitted from our list.

We should note that we have not considered pre-main sequence stars in our analysis. This is for two principal reasons. First, given their fully convective nature, it is not certain that the activity-rotation period relationship of Noyes et al. (1984) (which was calibrated for main-sequence stars) holds, indeed an entirely different stellar dynamo mechanism may operate in pre-main sequence stars (e.g. Scholz et al. 2007). Second, radius estimates for pre-main sequence stars are also notoriously unreliable, since they depend upon age estimates which are uncertain by a factor of several (e.g. Naylor 2009; Baraffe, Chabrier & Gallardo 2009).

2.1 Adopted stellar parameters and errors

In order to determine $\sin i$ via equation 2, we have taken a weighted mean of the entries in Table 1 for the final values of $v \sin i$ and R_*. In identical fashion to that carried out in Watson et al. (2010), where no error was quoted on a published $v \sin i$ value we have taken it to be 1.0 kms^{-1} (twice the typical error assumed on $v \sin i$ measurements, see the catalogue of Fischer & Valenti 2005 for example). Regarding published radii with no associated error bar, we have taken the error to be 10 or 20 per cent of the absolute value. The choice between 10 or 20 per cent is taken to ensure that radii estimates with associated error bars were given a higher weighting than those without formal errors.

For stars with photometrically derived rotation periods which have no associated error bar, we have taken the error to be 10 per cent. This is commensurate with the typical error bars quoted on such measurements. Where available, photometrically derived rotation periods are adopted, otherwise the rotation period is estimated from the strength of the Ca II H and K emission (Noyes et al. 1984). Again, following Watson et al. (2010), for each $\log R'_{HK}$ measurement reported in Table 1 we have determined, where possible, the number of observations and period over which they were carried out (see Table 5). Where details are not present, or are ambiguous, we have assumed they are from a single observation and have flagged them as *'individual?'*. As in Watson et al. (2010), each star was assigned a grade of P (Poor), O (O.K.), G (Good) or E (Excellent) based on how well monitored it was. We then assigned general error bars on the $\log R'_{HK}$ values dependent on their assigned grades and spectral type. These error bars are derived from the *average rotationally modulated variations* outlined in Section 3.1 of Watson et al. (2010). For a detailed discussion of the systematic errors on the derived parameters, we refer the reader to this work.

2.2 Determining the stellar inclination angle

Equation 2 can be thought of as a naive estimator of $\sin i$ as it is geometrically unconstrained (e.g. $\sin i > 1$ is allowed). While a value of $\sin i > 1$ is unphysical, it does allow potential problem cases to be identified. Table 2 shows the adopted parameters for each star, plus the naive $\sin i$ estimation alongside the formal error bar. Again, we follow Watson et al. (2010) and reject systems with $\sin i$'s that are 1-σ greater than 1 from further analysis – flagging these as having a high probability of being affected by systematic errors. This results in the omission of 2 systems, HD 53143 and HD 139664, both of which have naive $\sin i$ estimates significantly greater than 1. In the case of HD 139664, the $B-V$ value places it at the extreme edge of the chromospheric emission – rotation period calibration by Noyes et al. (1984). In addition, the star is classified as having a luminosity class IV, and therefore both the derived rotation period from the Noyes et al. (1984) relationship (which is only calibrated for main-sequence stars) and radius may also be suspect. HD 53143, on the other hand, is more problematic. It appears to have a secure rotation period which has been measured photometrically and that also agrees very well with the period derived from the Ca II H and K emission. In addition, all of the measured $v \sin i$'s and radii are consistent with one another. Yet, despite this and the fact that it appears to be a solid main-sequence star with an age of 1.0 ± 0.2 Gyr (Kalas et al. 2006), we derive $\sin i \sim 1.5 \pm 0.4$. We can only assume that 1 or more of the measurements are affected by systematics.

For the 8 remaining systems we have carried out a Markov-chain Monte Carlo (MCMC) analysis which not only provides a means of optimising the fit of a model to data but explores the joint posterior probability distribution of the fitted parameters and allows proper 1-σ two-tailed confidence limits to be placed on the derived $\sin i$'s. In addition, MCMC rejects unphysical combinations of parameters that result in $\sin i > 1$. For the purposes of this work, we have followed the MCMC process outlined in Watson et al. (2010), keeping the same 1000-step burn-in phase and carrying out 1,000,000 jumps. The results of this MCMC analysis are shown in Table 3.

3 RESULTS AND DISCUSSION

Table 4 shows our derived stellar rotation inclination angles versus published debris-disk inclinations. As can be seen, there is no obvious evidence for large mis-alignments of the stellar rotation axes and debris-disk planes in any of these systems. By the nature of the method, the best constrained systems have $\sin i \sim 0.5$ ($i_* = 30°$). This is because at high inclinations the sine curve is relatively flat, and thus small errors in $\sin i$ (which is what is directly calculated from the observables in equation 2) propagate to form large errors when expressed in degrees. At $\sin i$'s of $\sim$0.5, the sine curve is much steeper, and travelling along the sine curve does not vary the inclination i_* as quickly as it does at high $\sin i$'s. As one moves to lower $\sin i$'s, measurement errors on $v \sin i$ naturally increase as the projected rotational broadening decreases. The fact that the best constrained systems, HD 22049 and HD 107146, with errors on i_* of only $5-9°$ appear to align closely with their debris disk gives us both confidence in the technique, and further strengthens our assertion that we see no evidence for a detectable difference between the sky-projected angle of the disc and the that of the stellar rotation axis. In addition, it should be noted that HD 22049 is known to host a planet that has had the inclination of its orbital plane accurately determined to be $i_{planet} = 30.^\circ1 \pm 3.^\circ8$ – suggesting coplanarity between the planetary orbit and disk (Benedict et al. 2006). Furthermore, star spot modeling of a MOST light curve of HD 22049 by Bryce et al. (2006) determined the inclination of the stellar rotation axis to be $i_* = 30° \pm 3°$, in excellent agreement with our derived values. We do caution, however, that the absolute direction of the axis (whether the rotation axis is pointing towards or away from the observer) cannot be ascertained, and therefore we do not have a knowledge of the full three-dimensional geometry of the star-disk systems.

We interpret our results as indicating that all 8 systems are well-aligned (since it would be a huge coincidence that both disk and star inclination angles would be identical, but pointing in opposite directions), we can use this to set limits on the percentage of misaligned systems that may exist. If ~ 30 per cent of star-disc systems are misaligned then the chance of drawing, at random, 8 aligned systems from this population is less than 0.06. The probability drops rapidly to 0.004 if we assume equal numbers of aligned and misaligned systems. A recent analysis of Rossiter-McLaughlin observations by Triaud et al. (2010) suggest that between 45 – 85 per cent of hot-Jupiters appear to be significantly misaligned. However, our work in this paper reveals no similar degree of misalignment between debris disks and their host stars. We conclude that there appears to be no substantial evidence to suggest that the process outlined by Lai et al. (2010) is a major mechanism in misaligning planetary orbits.

Table 1: Published data on the properties of 10 stars hosting resolved debris disks. Rotation periods quoted with no reference have been calculated using the adjacent $\log R'_{HK}$ entry using the Noyes et al. (1984) chromospheric emission – rotation period relationship along with $(B-V)$ values taken from NStED.

HD (1)	HIP (2)	Alternative Name (3)	$v \sin i$ (km s^{-1}) (4)	σ_v (5)	$\log R'_{HK}$ (6)	P_{rot} (days) (7)	σ_p (8)	Radius ($R_\odot$) (9)	σ_r (10)
10647.....	7978....		5.600[2]	0.500	-4.68[8]	7.562	...	1.080[1]	0.050
			6.000[4]	...	-4.700[9]	7.903	...	0.990[12]	...
			4.880[8]	...	-4.714[11]	8.137	...	1.096[13]	0.025
			5.200[11]	...	...	...	...	1.14[14]	0.040
10700.....	8102....	TAU Cet	1.300[2]	0.500	-4.980[3]	32.848	...	0.750[1]	0.030
			1.000[4]	...	-4.955[5]	32.058	...	0.880[17]	0.100
			0.800[7,a]	0.400	-4.958[22]	34.00[22,p]	...	0.830[14]	0.020
			2.000[24]	...	-4.955[23]	32.058	...	...	...
			0.400[25]	0.400	-5.026[11]	34.266	...	...	...
22049.....	16537...	Epsilon Eri	2.400:[2]	...	-4.510:[3]	17.275:	...	0.740:[1]	0.030
			1.700[25]	0.300	-4.455[22]	12.000[22,p]	...	0.860[17]	0.120
			1.800[7,a]	0.400	...	11.300[26,p]	1.100	0.690[12]	...
			...	...	...	11.150[27,p]	1.150	0.770[14]	0.020
			...	...	...	11.300[23,p]	...	...	...
53143.....	33690...		4.000[4]	...	-4.520[5]	16.298	...	0.920[1]	0.050
			4.100[11]	...	-4.507[11]	15.528	...	0.880[12]	...
			4.000[10]	...	...	16.400[18,p]	...	0.870[17]	...
			...	...	...	...	...	0.850[13]	0.020
61005.....	36948...		9.000[4]	...	-4.260[5]	3.677	...	0.810[12]	...
			8.200[11]	...	-4.324[11]	5.551	...	0.840[1]	0.06
			...	...	-4.360[15]	6.826	...	...	...
			...	...	-4.337[16]	5.993	...	...	...
92945.....	52462...	GJ 3615	4.000[4]	...	-4.320[3]	6.964	...	0.810[1]	0.050
			5.100[2]	0.500	-4.393[16]	10.446	...	0.780[14]	0.030
			5.100[7,a]	2.100	...	13.470:[21]	...	0.770[12]	...
			4.000[10]	...	...	...	...	...	...
107146..	60074..		5.000[2]	0.500	-4.340[3]	3.496	...	0.990[1]	0.070
			5.000[4]	...	...	...	...	0.981[2]	0.027
			...	...	...	...	...	1.000[14]	0.040
			...	...	...	...	...	1.000[13]	0.020
			...	...	...	...	...	0.970[12]	...
139664..	76829.....	GJ 594	71.600[6]	3.600	-4.621[11]	1.517	...	1.33[1]	0.060
			105.000[7]	...	...	...	...	1.270[17]	0.500
			87.000[19]	...	...	...	...	1.318[13]	0.030
			...	...	...	...	...	1.260[12]	...
197481....	102409..	AU Mic	9.300[10]	1.2	-4.520[5]	4.865[21,p]	...	0.870[1]	0.020
			8.000:[7]	...	...	4.850[18,p]	...	0.860[12]	...
			...	...	...	4.822218[20,p]	...	0.610[17]	0.050
207129	107649	GJ 838	2.000[4]	0.000	-4.800[5]	15.171	...	1.040[1]	0.050
			2.400[2]	0.500	-4.850[9]	16.296	...	0.985[17]	...
			...	...	-5.020[16]	19.536	...	1.080[14]	0.040
			...	...	...	...	...	1.047[13]	0.024
			...	...	...	...	...	0.980[12]	...

References: [1]NStED, [2]Valenti & Fischer (2005), [3]Wright et al. (2004), [4]Nordström et al. (2004), [5]Henry et al. (1996), [6]Reiners & Schmitt (2003), [7]Glebocki & Stawikowski (2000), [8] Coralie, [9]Jenkins et al. (2006), [10]Torres et al. (2006), [11]Schröder, Reiners & Schmitt (2009), [12]Rhee et al. (2007), [13]Allende Prieto & Lambert (1999), [14]Takeda et al. (2007), [15]White et al. (2007), [16]Gray et al. (2006), [17]Fracassini et al. (2001), [18]Pizzolato et al. (2003), [19]Ochsenbein & Halbwachs (1999), [20]Pojmański & Maciejewski (2005), [21]Samus et al. (2009), [22]Baliunas et al. (1996), [23]Noyes et al. (1984), [24]Mallik et al. (2003), [25]Saar & Osten (1997), [26]Simpson et al. (2010), [27]Fray et al. (1991)

: = value uncertain. [a] = mean of a range of values given by Glebocki & Stawikowski (2000). [p] = rotation period measured photometrically.

Table 2: Adopted parameters and 'naive' $\sin i$ estimates as derived from equation 2, complete with formally propagated errors.

HD or Alt. Name (1)	$v \sin i$ (km s^{-1}) (2)	σ_v (3)	P_{rot} (days) (4)	σ_P (5)	R_* ($R_\odot$) (6)	σ_R (7)	$\sin i$ (8)	$\pm$ (9)
10647	5.497	0.377	7.803	1.32	1.099	0.019	0.770	0.115
10700	0.848	0.232	34.000	3.399	0.807	0.016	0.706	0.206
22049	1.772	0.233	11.300	0.510	0.770	0.019	0.513	0.072
53143	4.033	1.000	16.399	1.639	0.850	0.019	1.536	0.412
61005	8.599	1.000	5.419	2.108	0.829	0.048	1.110	0.455
92945	5.022	0.468	7.176	2.830	0.786	0.024	0.905	0.368
107146	5.000	0.447	3.496	1.35	0.993	0.014	0.347	0.107
139664	89.711	1.827	1.517	0.249	1.319	0.026	2.038	0.339
197481	8.832	0.960	4.846	0.20	0.835	0.018	1.012	0.112
207129	2.319	0.447	17.129	1.610	1.048	0.018	0.748	0.161

Table 3: Results of the Markov-chain Monte Carlo analysis for the 8 stars which have acceptable naive $\sin i$ estimates. Column 8 gives the final derived $\sin i$ value, followed by the 1-σ two-tailed confidence limits.

HD or Alt. Name (1)	$v \sin i$ (km s^{-1}) (2)	σ_v (3)	P_{rot} (days) (4)	σ_P (5)	R_* ($R_\odot$) (6)	σ_R (7)	$\sin i$ (8)	σ_- (9)	σ_+ (10)
10647	5.497	0.377	7.803	1.32	1.099	0.019	0.768	0.142	0.157
10700	0.848	0.232	34.000	3.399	0.807	0.016	0.702	0.208	0.229
22049	1.772	0.233	11.300	0.510	0.770	0.019	0.510	0.071	0.081
61005	8.599	1.000	5.419	2.108	0.829	0.048	0.999	0.123	0.000
92945	5.022	0.468	7.176	2.830	0.786	0.024	0.908	0.091	0.087
107146	5.000	0.447	3.496	1.35	0.993	0.014	0.353	0.141	0.138
197481	8.832	0.959	4.846	0.20	0.835	0.018	0.999	0.062	0.000
207129	2.319	0.447	17.129	1.610	1.048	0.018	0.746	0.167	0.187

Table 4. Comparison of the derived stellar rotational axes and published disk-plane inclinations. For HD 10647 and HD 10700 the lower value for the disk inclination corresponds to that derived from the observed disk dimensions and which we take to be the most probable value. References for the disk inclinations are given in the final column.

HD	i_* (°)	i_{disk} (°)	ref.
10647	49^{+17}_{-11}	$\geqslant$52	(Liseau et al. 2008)
10700	45^{+24}_{-15}	60–90	(Greaves et al. 2004)
22049	31^{+5}_{-5}	25	(Greaves et al. 1998)
61005	90^{+0}_{-26}	80	(Maness et al. 2009)
92945	65^{+21}_{-10}	70	(Krist et al. 2005)
107146	21^{+8}_{-9}	25±5	(Ardila et al. 2004)
197481	90^{+0}_{-20}	90	(Krist et al. 2005)
207129	47^{+22}_{-13}	60±3	(Krist et al. 2010)

Table 5: Compilation of chromospheric indices ($\log R'_{HK}$) for the stars in Table 1 for which no measured rotation periods have been reported. The spectral type of the host star is given in column 2. Entries in bold give the grade assigned to each star (P = Poor, O = O.K., G = Good, and E = Excellent) followed by the weighted mean of the $\log R'_{HK}$ measurements and adopted error bar (see section 2.1 for details). Reference numbers are identical to those used in Table 1.

Name	Type	log R'_{HK}	Observations	Ref.
HD 10647	F8V	-4.680	individual?	8
		-4.700	individual on 2001 Aug 04	9.
		-4.714	individual?	11.
			(P) Adopted value: -4.698 ± 0.060	
HD 61005	G3/5V	-4.260	1 obs on UT 14/12/1992	5
		-4.324	individual?	11
		-4.360	1 obs on 28/10/2002	15
		-4.337	individual?	16
			(P) Adopted value: -4.320 ± 0.075	
HD 92945	K1V	-4.320	13 obs in 6 months. Report $\sigma = 2.72\%$	3
		-4.393	individual?	16
			(O) Adopted value: -4.325 ± 0.077	
HD 107146	G5	-4.340	8 obs in 5 months. Report $\sigma = 3.04\%$	3
			(O) Adopted value: -4.340 ± 0.057	
HD 139664	F3/5V	-4.621	individual?	11
			(P) Adopted value: -4.621 ± 0.060	
HD 207129	G0V	-4.800	1 obs on UT 28/06/1993	5
		-4.850	1 obs on 2004 Aug 23/24	9
		-5.020	individual?	16
			(P) Adopted value: -4.89 ± 0.075	

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